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Local land-use change based risk estimation for future glacier lake outburst flood

Nussbaumer, Souria ; Huggel, Christian ; Schaub, Yvonne ; Walz, Ariane

Abstract: Effects of climate change are particularly strong in high-mountain regions. Most visibly, glaciers are shrinking at a rapid pace, and as a consequence, glacier lakes are forming or growing. At the same time the stability of mountain slopes is reduced by glacier retreat, permafrost thaw and other factors, resulting in an increasing risk of landslides which can potentially impact lakes and therewith trigger far reaching and devastating outburst floods. To manage risks from existing or future lakes, strategies need to be developed to plan in time for adequate risk reduction measures at a local level. However, methods to assess risks from future lake outbursts are not available. It is actually a challenge to develop methods to evaluate both, future hazard potential and future damage potential. Here we present an analysis of future risks related to glacier lake outbursts for a local site in southern Switzerland (Naters, Valais). To estimate two hazard scenarios, we used glacier shrinkage and lake formation modelling, simple flood modelling and field work. Further we developed a land-use model to quantify and allocate land-use changes based on local-to-regional storylines and three scenarios of land-use driving forces. Results are conceptualized in a matrix of three land-use and two hazard scenarios for a time period of 2045, and show the distribution of risk in the community of Naters, including high and very high risk areas. The study corroborates the importance of land-use planning to effectively reduce future risks related to lake outburst floods.

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Local land-use change based risk estimation for future glacier lake outburst flood

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Abstract

Effects of climate change are particularly strong in high-mountain regions. Most visibly, glaciers are shrinking at a rapid pace, and as a consequence, glacier lakes are forming or growing. At the same time the stability of mountain slopes is reduced by glacier retreat, permafrost thaw and other factors, resulting in an increasing risk of landslides which can potentially impact lakes and therewith trigger far reaching and devastating outburst floods. To manage risks from existing or future lakes, strategies need to be developed to plan in time for adequate risk reduction measures at a local level. However, methods to assess risks from future lake outbursts are not available. It is actually a challenge to develop methods to evaluate both, future hazard potential and future damage potential.

Here we present an analysis of future risks related to glacier lake outbursts for a local site in southern Switzerland (Naters, Valais). To estimate two hazard scenarios, we used glacier shrinkage and lake formation modelling, simple flood modelling and field work. Further we developed a land-use model to quantify and allocate land-use changes based on local-to-regional storylines and three scenarios of land-use driving forces. Results are conceptualized in a matrix of three land-use and two hazard scenarios for a time period of 2045, and show the distribution of risk in the community of Naters, including high and very high risk areas. The study corroborates the importance of land-use planning to effectively reduce future risks related to lake outburst floods.

1 Introduction

As a result of climate change high-mountain systems worldwide are changing at a rapid pace (Voigt et al., 2011; WGMS and UNEP, 2008; Clague et al., 2012). Glacier shrinkage is the most visible indicator of change (Gardner et al., 2013) but permafrost thaw has similarly been observed in many regions (Harris et al., 2009). For the Alps a drastic reduction of glacier extent and volume is projected for the 21st century (Zemp et al.,

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2007; Huss et al., 2008; Linsbauer et al., 2013). Climate induced changes involve a number of hazards, including unstable slopes, landslides and debris flows, landslides and avalanches impacting high-mountain lakes and therewith triggered outburst floods from recent or new glacier lakes (Stoffel and Huggel, 2012; Haeberli, 2013).

5 Many cases during the past several decades document the damages of glacier lake outburst floods (GLOF) on people and assets. Single events killed up to several thousand people and caused damages on the order of tens of millions USD (Clague and Evans, 2000; Carey, 2005; Huggel et al., 2011).

10 In Switzerland new glacier lakes that are forming or will form in the future in some glacially carved topographic depressions, parallel to glacier retreat, are of particular concern (Künzler et al., 2010). Glacier shrinkage and ice thickness modelling studies were able to indicate potential sites of future glacier lake formation over large parts of the Swiss Alps (Frey et al., 2010; Haeberli and Linsbauer, 2013). Many of them will be located in an unstable environment, e.g. underneath steep, destabilized slopes and are
15 therewith prone to impacts from mass movements which could trigger a GLOF. In the densely populated Swiss valleys such an event would be seen alongside large damage potential. To adequately handle these situations, the new lakes should be included into risk management as early as possible, given that planning of mitigation measures often requires a lot of time.

20 As for the hazard estimation, statistical and empirical methods have been developed to estimate the probability and intensity of glacier lake outbursts (Huggel et al., 2004; McKillop and Clague, 2007). To more accurately estimate the spatial distribution of the outburst flood and the aggregated inundation intensities, numerical models have been proved useful in several case studies (Huggel et al., 2003; Osti and Egashira, 2009; Künzler et al., 2010; Worni et al., 2012). First rough-scale modelling of outburst floods
25 have already been performed for future lakes in Switzerland (Frey et al., 2010), but there is a lack of assessment of future damage potential and therewith related risks of GLOFs.

for these scenarios, changes were related directly to drivers of land-use change, similar to Alcamo (2001). Rule based modelling then provides transparency in the allocation of land-use change. Here, we aimed for a high degree of thematic differentiation within the settled area. This degree of differentiation is highly desirable for local risk assessment, as it gives improved indication on future values and persons at risk (cf. BAFU, 2011a).

2 Study area and data

Naters is a municipality in the canton Valais in Switzerland at an altitude of 673 m a.s.l. It is a typical Swiss dormitory town, most of the people work in bigger towns nearby. In the last decade a considerable increase in population has taken place, as Naters has become a zone of attraction, especially to people from adjacent small villages. About 90 % of the Naters' 8300 inhabitants live in the valley bottom where also extensive agriculture is conducted. The valley is crossed by the rivers Rhône and Massa and is surrounded by steep slopes (BFS, 2011a) (Fig. 1a). The Massa flows from the reservoir lake Gibidum, which retains the melt water of the Aletsch glacier, to Naters.

Information on the potential location and approximate volume of future melt-out lakes in the Aletsch glacier area, draining towards Naters, were taken from recent studies investigating glacier bed topography and simulating glacial retreat over the next several decades (Linsbauer et al., 2013). These data was available in GIS format and represented the starting zones for potential GLOFs. As outlined in Fig. 1a, the risk study area concentrates on the Massa river channel and the flat part of Naters, where most people live. It is defined by the intensity maps of potential GLOF outbursts based on Linsbauer et al. (2013), including outburst scenarios of 4 million m³ (Fig. 1b) and 20 million m³ (Fig. 1c).

Interviews with local authorities, including the local planning department and a government representative, were conducted in July 2011 to better understand processes and limitations of land-use change in the municipality of Naters.

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As a basis for modelling spatially explicit future storylines of land-use change within the region, national survey data were used from two survey periods in 1979–1985 (BFS, 1986) and 1992–1997 (BFS, 1998). The Swiss land-use statistics differentiate originally between 72 land-use categories (BFS, 2011c). For this study, the data was reclassified into nine classes (Table 1). This process was facilitated by both, the literature review and the interviews with the local authorities. “Multi-family house”, “single-family house”, “mixed-use” (such as business buildings or parks), “industry”, “railway”, “roads”, “agriculture”, “forest” and “unproductive area” (such as water bodies or bedrock) were identified the most important categories with relevance to past and future changes in local land-use to estimate damage potential due to possible future GLOFs.

The Swiss land-use statistics were complemented until 2009 through land-use change mapping based on a field survey, the interviews with local authorities and the most recent topographic maps (swisstopo, 2011).

Estimation of economic values of the different land-use classes were adopted from the official Swiss platform for assessment of efficiency of protection measures against natural hazards (BAFU, 2011a) “EconoMe”. The visualization of the socio-economic scenarios and the GLOF modelling was rested upon the digital elevation model DHM25, based on the geodata of swisstopo (2010).

3 Methodology

In order to estimate the risk of a GLOF in Naters for future conditions, a three-step methodology was developed (Fig. 2). First, socio-economic scenarios were generated and different driving forces identified and quantified. This information was implemented in a second step into the land-use scenario modelling. Finally, corresponding risk estimates were made by integrating the modelled socio-economic scenarios and flood hazard.

3.1 Socio-economic scenario development for land-use changes in Naters

The exploratory scenarios (cf. Carter et al., 2001) were developed (Fig. 3) following the approach of Wissen et al. (2011). The goal of the present scenario development was to elaborate plausible land-use storylines for the municipality of Naters until 2045 which cover a wide range of fundamental uncertainties in regional socio-economic development and associated land-use changes. The extrapolation of the current state of land-use served as a baseline scenario.

The most relevant drivers of regional development and land-use changes and the potential development pathways for Naters were identified based on a literature review (CIPRA, 2010; OcCC, 2007; Müller, 2005; BUWAL, 2003; ARE and UVEK, 2005; IPCC, 2012; Voigt et al., 2010; de la Vega-Leinert and Schröter, 2004), interviews with the local planning authorities and the government representative (oral statement Michlig, 2011; oral statement Holzer, 2011). The drivers and the development pathways were then combined to three land-use scenarios. The scenario storylines could per se not be validated, but plausibility checks were performed by cross-checking the scenarios with other scenarios for Swiss mountain regions (ARE and UVEK, 2008; Leitungsgruppe des NFP 48, 2007; Wissen et al., 2011; Walz et al., 2007; Lauber et al., 2006; Müller and Weber; 2008).

3.2 Land-use modelling: quantification and allocation of change

Similar to other studies (cf. Walz et al., 2007), land-use modelling was performed by first quantifying land-use transition rates and then allocating changes in space.

Quantification of land-use change

Methods to quantify land-use change based on socio-economic scenario are manifold. Potential approaches include, for instance, in participatory processes (cf. Walz et al., 2007), economically-based modelling (cf. Britz et al., 2011; Briner et al., 2012),

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agent-based modelling techniques (cf. Fontaine and Rounsevell, 2009), and conditional extrapolation of recent trends (cf. Soares-Filho et al., 2006). In the present study, the three socio-economic scenarios were translated to land use change rates by (a) extrapolation of the observed changes for the scenario “o” and (b) by conditional adaptation of these rates based on the quantification in driving forces in the socio-economic scenarios for the scenarios “+” and “–”.

Here, land-use transition rates were estimated for two 12 yr steps (1997–2009 for validation and 2009–2021) followed by a 24 yr step (2021–2045). The 24 yr step was chosen to allow for an overall rate of change and to avoid further uncertainties. For that, we first extrapolated observed transition rates from past changes between the two available land-use data sets for the trend scenarios (scenario “o”) (BFS, 1986; BFS, 1998). These rates, however, were limited to the legal planning constraints in particular relevant for settlement expansion (oral statement Michlig, 2011). For the two further scenarios (scenario “+” and scenario “–”), rates of land use change were estimated by quantifying driving forces based on the assumption in the socio-economic scenarios. Again, these rates were limited to legal constraints.

We assume a constant building density for all cells of the settlement related land use classes.

Interaction between land-use classes

Changes in single land-use classes, hereby, interacted with changes of other land-use classes where expansion of one land-use class happened at the cost of another one. “Agriculture” and “settlements” as an example interacted highly with each other, “forest” interacted with “agriculture” and “industry”, “roads” interacted partly with “settlements”. Within the “settlements” the increase of “mixed-use” areas was highly dependent on the increase of “multi-family houses” and “single-family houses”: an increasing number of inhabitants also requires e.g. more businesses, schools or retreat homes.

The plausibility of the resulting transition rates was tested by comparing the defined rates of change to recent studies of Swiss land-use changes. These studies were

also consulted to determine the transformation rates between certain land-use classes (e.g. from “agriculture” to “mixed-use”) (Walz et al., 2007; BUWAL, 2003; ARE and UVEK, 2008; Leitungsgruppe des NFP 48, 2007; de la Vega-Leinert and Schröter, 2004; OcCC, 2007; Perlik et al., 2008; CIPRA, 2010).

5 Allocation of land-use change

The final modelling step of land-use allocation was to determine the cells to be changed into another land-use class.

Future changes for the validation period 1997–2009 and the future period until 2045 were allocated by a rule-based transition model.

- 10 – Based on legal constraint (ARE and UVEK, 2008), only cells within the current legally defined construction areas could be transformed to any kind of settlement (including “multi-family houses”, “single-family houses” and “mixed-use”) as no adaptation of the legally defined construction areas was assumed for the future (oral statement Michlig, 2011).
- 15 – Due to topography and lifetime, certain land-use classes were assumed constant (i.e. “unproductive areas”, “roads”, “railways” or “bridges”), and certain land-use classes could only be changed into one direction, i.e. “agriculture” to “settlements” and “settlements” to “settlements”. One exception are “roads” and “unproductive areas” within areas with housing settlements, here an aggregation of the settle-
20 ments provokes a change within the “roads” or “unproductive area” cell transform-
ing it into settlement.
- Additionally, the transition into certain land use classes was determined by land use of the neighbouring cells to support clustering of same land use in line with the federal land-use planning guidelines (ARE and UVEK, 2008).

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For validation the simulated trend scenario between 1997–2009 was compared with the most recent topographical maps based on 2009 aerial photographs (swisstopo, 2011).

3.3 Risk estimation

Quantitative risk analysis (Bouwer et al., 2010; Aerts et al., 2013) require information on event probabilities. As knowledge on GLOF probabilities is still very limited, a semi-quantitative risk estimation (van Westen et al., 2006; UNISDR, 2009) was considered more appropriate for the present case study, as it avoids introducing additional assumptions.

For this purpose, the risk formula of Bründl et al. (2009) was adapted as follows:

$$R = I \cdot S \cdot V$$

Where R = risk; I = intensity; S = object value/persons; and V = vulnerability.

For each of these assessment variables, values were assigned to each grid cell of an ArcGIS raster, applying the four level scale 1 = “low”, 2 = “medium”, 3 = “high”, 4 = “very high”.

Intensity (I):

Recent studies indicate that new lakes with volumes up to 170 millionm³ may form in the area of Grosser Aletsch glacier over the next 100 yr as a result of glacier retreat (Linsbauer et al., 2013). For the purpose of the present study, an outburst of a potential new lake, which is expected to have reached a volume of about 20 millionm³ until 2045 (Linsbauer et al., 2013), was assumed (Fig. 1a). The exact lake outburst mechanisms obviously cannot be predicted but both, evidence of existing landslides (Strozzi et al., 2010) and an expected further destabilization of slopes due to glacier retreat (Haeberli et al., 2010; Künzler et al., 2010; Huggel et al., 2012; Schaub et al., in press), suggest

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that impacts from landslides into the lake and therewith produced displacement waves and outburst floods may be a realistic scenario.

In a first stage a simple flow-routing model was applied (Huggel et al., 2003) to assess the approximate extent of downstream flooding for a lake outburst from the identified lake. The uncertainties related to future lake formation and potential catastrophic drainage suggested the use of outburst scenarios. Accordingly, we defined two outburst flood scenarios based on two different outburst volumes for the same lake, 4 million m³ and 20 million m³, representing partial and full drainage, respectively. Intensity layers for each outburst scenario with different intensities depending on the height of the flooding (cf. Loat and Petracheck, 1997) were then evaluated in the field and in GIS based on the calculation of the maximum flood runoff after Huggel et al. (2002) and the flow capacity of open channels and overspill after Henderson (1966).

Finally two different intensity classes were distinguished for both outburst flood scenarios. These classes were built on the official Swiss guidelines (Loat and Petracheck, 1997) and differentiate between “high intensity” for an inundation height of > 2 m and “medium intensity” for inundation height < 2 m (Fig. 1b and c).

Loss (S):

Since all variables were classified qualitatively and were not monetized, the variable loss was divided into object value and number of persons exposed. Scores for the object values were taken from the EconoMe database (BAFU, 2011a). For persons the scores were estimated depending on the population density per land-use class. Independent of each other, object values and persons were ranked and further semi-quantitative loss scores then assigned to the ranked land-use classes taking in account similar value boundaries (Table 4). The mean value of both variables then formed the factor loss.

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Vulnerability (V):

The definition and use of vulnerability varies depending on the conceptual approach and its relation to risk (cf. ATEAM, 2004; UNISDR, 2009; Dow, 1992; Cutter et al., 2009). In the present study it was differentiated between physical (cf. BAFU, 2011b) and social vulnerability (cf. Bara, 2010; IPCC, 2012; Hegglin and Huggel, 2008) following Cutter et al. (2009).

For classifying social vulnerability two different approaches were applied. On the one hand a value was given for each land-use class as a function of its insurance cover. This classification (Fig. 4) resulted in a high and very high vulnerability for “settlements”, “mixed-use” and “industry”, whereas a low or medium value was allocated to “roads”, “railway”, “forest”, “agriculture” and “unproductive area”. Land-use classes featuring good financial coverage were classified as less vulnerable than those not covered by insurance. The allocated values represent the ability of affected persons to recover from disasters and were estimated based on literature (cf. Nöthiger et al., 2002; Kantonsforstamt St. Gallen, 2011; Burgerschaft Naters, 2011; BFS, 2011c; OcCC, 2007; Hausmann, 1998; Voigt et al., 2010; Mills, 2004; CIPRA, 2010). Hence “multi-family houses” were classified more vulnerable than “single-family houses”, because in “multi-family houses” there are more young, poor, old, foreign and separated people living (oral statement Michlig, 2011). They either cannot afford a good insurance or are not in a position to get a one, for instance due to comprehension problems (Bara, 2010).

On the other hand particularly vulnerable locations were flagged in the final risk map (Fig. 6) such as schools, churches or sports ground (cf. Bara, 2010).

The values for physical vulnerability with respect to high-intensive debris flows were derived from EconoMe (BAFU, 2011a) and applied to each land-use class. The values of “mixed-use”, “streets”, “industry”, “railway” and “unproductive area” were estimated by taking the average of the existing values similar to the land-use class (e.g. values for streets (0.7) were represented in EconoMe by values for motorways (0.45), municipal roads (0.95) and rural roads (1)). To be consistent with the other semi-quantitative

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input grids to the final risk assessment, the assigned scores had to be reclassified to a four level semi-quantitative scale, as the values from EconoMe vary between 0, equal to lowest vulnerability corresponding to no loss, and 1, equal to maximal vulnerability corresponding to total loss. This classification (Fig. 4) resulted in a very high and high physical vulnerability, respectively, for “agriculture”, “forest” and “unproductive area”, as well as “settlements” and “railway”, while “roads” were classified as medium, and “mixed-use” and “industry” as little vulnerable. The final vulnerability value is the mean value of both physical and social vulnerability.

Risk (R):

For the final risk assessment all layers were multiplied according to Eq. (1). As a result, six risk maps were generated covering all three socio-economic scenarios and both lake outburst scenarios.

4 Results

4.1 Socio-economic scenarios

The reclassified land-use data set from 1997 shows an increase in “settlements” of 63 % or 12 ha and a decrease in the category “agriculture” of –18 % or 14 ha as compared to 1985 (Fig. 4). Further field surveys, the interviews with the local authorities and recent topographic maps (swisstopo, 2011) in fact document a continuing increase of settlements and decrease of agriculture after 1997 in Naters. In reference to that information the following driving forces that have the most important influence on land-use changes in settlements and agriculture were chosen for the scenarios in Naters:

- Agriculture: the steep slopes in Naters, with extensive agriculture, are subsidized by the government. A cutback of the subsidies would lead to abandonment of

the agriculture land and imply growing forest areas as well as an unattractive landscape, which both leads to less tourism in the area.

- Economic situation: Naters has experienced an economic upturn during the last 15 yr which led amongst others to a strong increasing construction in the area. A possible stagnation of the national economic situation would slow down the construction activities, a downturn highly constrain them.
- Tourism: tourism and economy are closely linked in Naters. An upturn in tourism would imply strong increasing businesses, a downturn abandoning businesses.

Three different scenarios, scenario “o”, scenario “+” and scenario “–”, resulted from these driving forces and their implications (Table 3), containing different interactions between the driving forces.

The storylines of the respective scenario are described as follows:

Scenario “o” is an approach of a business-as-usual scenario, respectively the continuation of the current state of land-use according to the ideas of the stakeholders of Naters, on how their community is most probably going to develop until 2045. There are no radical changes foreseen in any land-use class. The trend of an increase in the category “settlements”, observed in the past at the expense of “agriculture” in the legally defined zone of construction, will continue for the next 10 yr. Especially “single-family houses” will rise in numbers, whereas in “mixed-use” a moderate growth is expected. In “multi-family houses” the least increase in settlements is predicted due to compaction of the construction. After 2021 the building construction will stabilize along with the economic development.

Scenario “+” is marked by a strong increase in building constructions until 2045, particularly within “single-family houses” and “mixed-use”, as a consequence of a stable and prosperous economic situation. The growing tourism sector will benefit from climate change since parts of the municipality Naters include high-elevation winter tourism areas, which are likely to attract tourists who used to visit lower situated ski destinations. This development will lead to an increase in business constructions as

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well as in new public buildings, such as schools or retirement homes amongst others. The area within the current construction zone which is not yet covered with buildings, will be developed mostly at the expense of the agriculture sector.

Scenario “–” is characterized by a decreasing settlement construction from 2021 on due to economic downturn. However, a few settlements will still be built, such as public buildings and “single-family houses”, from those people who are not negatively affected by the economic crisis. The tourism sector will decrease, implying abandonment of businesses locations. Furthermore subsidies to agriculture will no longer be provided by the government. As a consequence, forest areas will increase and landscape may lose attractiveness (Hunziker, 1995), which again might result in a decrease in tourism.

4.2 Land-use modelling: quantification and allocation

Table 4 shows the results of the quantified driving forces. The percentage in change for each time step relates to the previous time step and not to the baseline.

All model runs for all scenarios and the whole time span show an increase in settlement, “multi-family houses”, “single-family houses” and “mixed-use”, between 3 % and 40 %. The increase of these changing rates however slowed down after 2009. Within each scenario there is regular increase or decrease according to the land-use class. Independent of the driving-scenario, “agriculture” lost a large amount of space for future time spans, it decreased even more than observed in the past. “Industry” decreased until 2045, if it was driven by the scenarios “o” and “+”. “Forest”, “unproductive area”, “railway” and “roads” did not show large changes between past and future time spans in any scenario. Generally, the rate of increase in specific land-use classes slows down with time due to the growth of their respective areas. The scenarios “o” and “+” had the same changes in all land use classes until 2021 and started to differ thereafter, whereas the scenario “–” developed independent characteristics from the beginning of modelling (2009) as it is the only scenario including economic downturn. The results of the modelled land-use scenarios in 2045 are shown in Fig. 4 in comparison to the land-use of Naters in 2009. All scenarios implied changes in similar land-use classes,

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mainly in settlement areas including “multi-family houses”, “single-family houses” and “mixed-use”. The changes were projected to take place mainly at the expense of “agriculture”. There was a strong increase in “single-family houses” in the eastern part of Naters, where construction was legally approved after 1997, particularly in the scenario “+”. “Multi-family houses” gained further on space and aggregated in the area along the Rhône river at the southern border of Naters, where they are already concentrated at present. The same development was also modelled for “mixed-use”, where already existing zones aggregated along the river in addition to increasing “mixed-use” areas in the center of the village.

4.3 Risk estimation

The flood intensity estimations showed (Fig. 1b and c), that the biggest part of the studied area will be affected in case of a GLOF, independent of the outburst scenario (4 million m³ or 20 million m³). The height of the flood varies between 1 m and approximately 14 m in narrow passages. In both GLOF scenarios a maximum estimated retention volume of 2 million m³ by the barrier lake Gibidum was considered. A volume of 1.5 million m³ overflowing Gibidum lake would be enough to reach areas in Naters with a high intensity. Accordingly, for the 4 million m³ scenario, high flood intensities (> 2 m inundation height) were modelled for at least half of the affected surface.

In all scenarios, the highest values for the factor loss were mostly modelled in the central part of Naters, where most “settlements” are located (Fig. 5). The most striking difference between values for persons and for objects can be seen in “mixed-use”, which varied between high (persons) and intermediate (object value) according to the classification presented in Table 2.

Only very few areas showed low or intermediate physical vulnerability against a GLOF in any scenario. Very high physical vulnerability, however, is predominantly present at the marginal areas of the case study area, as it mostly belongs to “forests”, “agriculture” and “unproductive areas”. “Multi-family houses” also feature very high physical vulnerability and are located in the areas very close to the river Rhône. Fur-

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thermore, virtually the entire centre of Naters showed high physical vulnerability, as it consists mainly of “single-family houses” and “mixed-use”.

The distribution of the social vulnerability, however, resulted in patterns very similar to the loss of persons and was therewith mainly modelled in the central part of Naters, with very high values in the areas of “multi-family houses”. Contrary to the value for physical vulnerability, marginal areas featured low social vulnerability.

The final risk maps (Fig. 6) showed high risk in each socio-economic and intensity scenario for a large area of Naters. In case of a GLOF of 20 million m³ a larger zone with higher risk was modelled than in the case of a GLOF of 4 million m³, where the overall risk resulted smaller and appeared mainly as low and intermediate risk (Table 5). For the 20 million m³ scenario and all socio-economic scenarios the percentage of the areas with very high risk at least doubled as compared to the scenario with the smaller GLOF. For low, intermediate and high risk, the differences were not that striking.

The area classified as very high risk was mostly accumulated near the river in middle of Naters for both GLOF scenarios and for all socio-economic scenarios. In the case of the 20 million m³ GLOF one additional very high risk zone was modelled in the middle of the village.

Interestingly, the spatial pattern of the different risk categories and corresponding relative and absolute areas are quite similar for the socio-economic scenarios “o” and “+”. For the scenario “-”, however, a clear reduction of very high risk areas from 13 % and 15 % for scenarios “o” and “+”, respectively, to 8 % for scenario “-” can be observed. Some of the very high risk areas in scenarios “o” and “+” changed to high risk in scenario “-”, a reason why scenario “-” has a larger area in this risk category. The objects of special interest and vulnerability are highlighted in Fig. 6 and include a church, school and hotel which are found in areas of medium to very high risk.

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5 Discussion and conclusions

In line with the objectives of this study we developed a method that is feasible to assess local-scale damage potential as defined by changing land-use conditions, and therewith future risks related to floods from GLOFs. An extensive review of existing methodologies revealed that there was no adequate approach available which could directly be applied for the purpose of this study. There exists an important body of research on land-use modelling including the assessment of driving forces, scenario development and allocation of change in space. Existing land-use models explore the possible changes in the future and at a range of scales but rarely with the primary objective of quantifying damage potential related to natural hazards.

On the other hand, recent studies modelled GLOF processes but mainly based on observed events or existing lakes (Osti and Egashira, 2009; Worni et al., 2012). Studies on the assessment of local-scale hazards from floods from future lakes are currently a research gap. Therefore, one of the main challenges of this study was to develop, adapt and apply methods from two different scientific fields, i.e. land-use change and GLOF research, to achieve the assessment of associated future risks.

The assessment of hazards related to outbursts of future glacier lakes involves substantial uncertainties. However, results from glacier shrinkage and lake formation modelling are relatively robust for a glacier of the size of Grosser Aletsch. As confirmed by multiple model runs the exact location of a future glacier lake (as subject to uncertainty) does not have a critical effect on flood intensities at Naters. Uncertainties related to GLOF volume were accommodated by defining different outburst scenarios, an approach that is also applied for present-day lake outburst flood hazards (Schneider et al., 2013) and that is generally recommended in situations of problematic knowledge on probabilities (Stirling, 2007).

Uncertainties are also substantial with respect to future damage potential, the second component of the risk equation. Similarly as for the hazard component, scenarios were defined to cover a range of different land-use story lines. To some degree defini-

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the new glacier lakes will form, may be of relevance (cf. IPCC, 2012). Experiences have shown that early warning systems for GLOFs can be effective means to achieve this risk reduction (cf. Kattelmann, 2003; Huggel et al., 2012), by mainly decreasing the number of persons exposed. The value and vulnerability of objects possibly affected, however, will remain unchanged. Avoidance of high-loss and high-vulnerability assets in flood prone areas is most important to reduce high/very high risks (cf. CIPRA, 2010; ARE and UVEK, 2008; Schwank et al., 2009), especially if structural mitigation measures might not be very feasible. The avoided damage can be estimated from our risk analysis based on the different scenarios.

Our study therewith corroborates the fundamental importance of land-use policies and governance for risk reduction (cf. BUWAL, 2003; IRV, 2008; OcCC, 2007). In case of high-development trajectories a main challenge for policy will be to counteract certain driving forces. This study can represent a contribution for local, rural development planning, if additional information on risks related to other natural hazards as well as the coordination with further development plans of the community is considered.

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Table 1. Reclassification of the land-use classes by BFS (2011c). The abbreviations will be used further on in the document. To simplify, MFH, SFH and Mix will also be merged to settlement.

Reclassified classes	land-use	Description (original land-use class number)
Multi-family house (MFH)		Multi-family houses, backyards (27, 47)
Single-family house (SFH)		Single-family houses, agricultural buildings, backyards, allotment gardens (25, 28, 45, 52)
Mixed-use (Mix)		Mixed-use, backyards, sports areas (29, 49, 51)
Settlement		MFH, SFH, Mix
Industry (Ind)		Industry, industrial railways, repositories, diggings (21, 41, 64, 65)
Railway (Rail)		Train station area, railways, green areas (35, 36, 67)
Roads (Road)		Roads, Parking lots, green areas (33, 34, 68)
Agriculture (Agri)		Sparse orchards, gardenings, meadows, pasture lands (77, 78, 81, 82, 83, 84, 85, 86, 87, 88, 89)
Forest (For)		Open and closed forests (11, 12, 13, 14, 15, 16, 17, 18, 19)
Unproductive area (Unprod)		Glaciers, Water, Rocks, open vegetations (90, 91, 92, 95, 97, 99)

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Table 2. Allocation of the assessment variables into a four-level scale. Intensity is defined by the inundation depth. Allocation of the land-use classes differs between object value and number of persons present for loss, and between physical and social vulnerability respectively.

Scale		Intensity Inundation	Loss Object value	Persons	Vulnerability Physical	Social
1	Low	< 2 m	Agri, For, Unprod	Agri, For, Unprod	Mix, Ind	Agri, For, Unprod
2	Intermediate		Mix, Ind, Road, Rail	Ind, Road, Rail	Road	Road, Rail
3	High		SFH	SFH, Mix	SFH, MFH, Rail	SFH, Mix, Ind
4	Very high	> 2 m	MFH	MFH	Agri, For, Unprod	MFH

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Table 3. The development pathways of major driving forces and their implications for land-use within the three scenarios “o”, “+” and “–”.

Driving forces	scenario “o”	scenario “+”	scenario “–”
Subsidization agriculture <i>implications for L/U</i>	business as usual decreasing agriculture	business as usual decreasing agriculture	cutbacks abandoning agriculture, increasing forest area
Economic situation <i>implications for L/U</i>	stagnation and downturn moderate increasing construction	stable strong increasing construction	downturn decreasing construction
Tourism <i>implications for L/U</i>	business as usual moderate increasing businesses	increasing strong increasing businesses	decreasing abandoning businesses

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Table 4. Changes in land-use for each scenario as a result of quantified driving forces, whereby italic indicating an increase and bold a decrease of the area. Each value in every time period relates (a) to the total number of cells of the previous time span and (b) to the percentage of land-use class of the total area per time span.

Timespan Scenarios		1985–1997 “o”/“+”/“–”	1997–2009 “o”/“+”/“–”	“o”	2009–2021 “+”	“–”	“o”	2021–2045 “+”	“–”
MFH	a	+13 %	+19 %	+13 %	+13 %	+10 %	+8 %	+17 %	–
	b	7.1 %	8.1 %	9.5 %	9.5 %	8.9 %	10.2 %	11 %	8.9 %
SFH	a	+33 %	+40 %	+29 %	+29 %	+18 %	+14 %	+33 %	+9 %
	b	5.3 %	7.4 %	9.5 %	9.5 %	8.7 %	10.8 %	12.6 %	9.5 %
Mix	a	+17 %	+18 %	+15 %	+15 %	+9 %	+11 %	+16 %	+3 %
	b	7.4 %	8.7 %	10 %	10 %	9.5 %	11 %	11.6 %	9.7 %
Ind	a	–8 %	–8 %	–18 %	–18 %	–	–8 %	–8 %	–
	b	3.2 %	2.9 %	2.3 %	2.3 %	2.9 %	2.1 %	2.1 %	2.9 %
Rail	a	–	–11 %	–	–	–	–	–	–2.1 %
	b	2 %	2.1 %	2.1 %	2.1 %	2.1 %	2.1 %	2.1 %	–
Road	a	+13 %	–6 %	+7 %	+7 %	–	–	–19 %	–
	b	3.5 %	3.2 %	3.5 %	3.5 %	3.2 %	3.5 %	2.7 %	3.2 %
Agri	a	–18 %	–20 %	–33 %	–33 %	–24 %	–37 %	–37 %	–36 %
	b	18.2 %	14.7 %	10.2 %	10.2 %	11.5 %	6.9 %	5 %	7.9 %
For	a	+ < 1 %	+ < 1 %	+ < 1 %	+ < 1 %	+ < 1 %	+2 %	–	+7 %
	b	35.2 %	35.5 %	35.7 %	35.7 %	35.7 %	36.2 %	35.7 %	38.3 %
Unprod	a	–	–3 %	–2 %	–2 %	–	–	–	–
	b	18.1 %	17.5 %	17.2 %	17.2 %	17.5 %	17.2 %	17.2 %	17.5 %

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Table 5. Affected area per risk category as well as per land-use and intensity scenario. Total case study area = 2.88 km². Values in percent only refer to the affected area.

Risk category	Scenario “o”				Scenario “+”				Scenario “–”			
	4 million m ³		20 million m ³		4 million m ³		20 million m ³		4 million m ³		20 million m ³	
	km ²	%	km ²	%	km ²	%	km ²	%	km ²	%	km ²	%
1 = low	0.41	14	0.34	12	0.39	14	0.32	11	0.40	14	0.37	13
2 = medium	0.35	12	0.49	17	0.34	12	0.47	16	0.38	13	0.38	13
3 = high	0.13	4	0.14	5	0.13	4	0.15	5	0.16	5	0.36	13
4 = very high	0.16	6	0.38	13	0.19	6	0.41	15	0.11	4	0.24	8
No value	1.83	64	1.53	53	1.83	64	1.53	53	1.83	64	1.53	53

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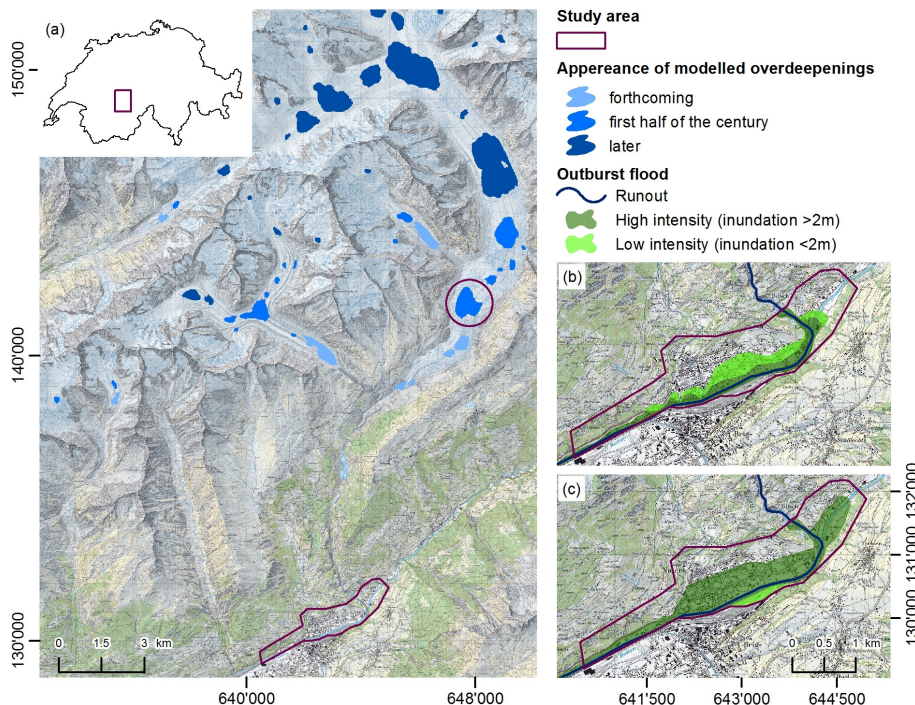



Fig. 1. Location of the risk study area in Naters, Switzerland and of modelled overdeepenings in the glacier beds in the Aletsch glacier area, which are assumed potential sites of future lake formation (Linsbauer et al., 2012) (a) integrating the intensity maps elaborated for the outburst scenarios of 4 million m³ (b) and 20 million m³ (c). DHM25 reproduced with permission of swisstopo (BA110005).

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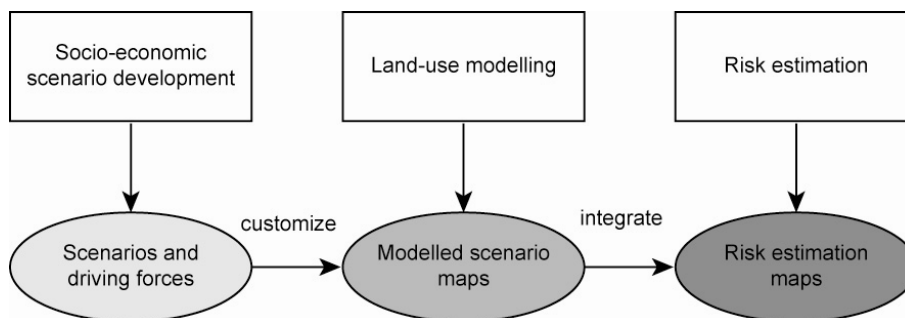
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**Fig. 2.** Simplified overview of the methodology.

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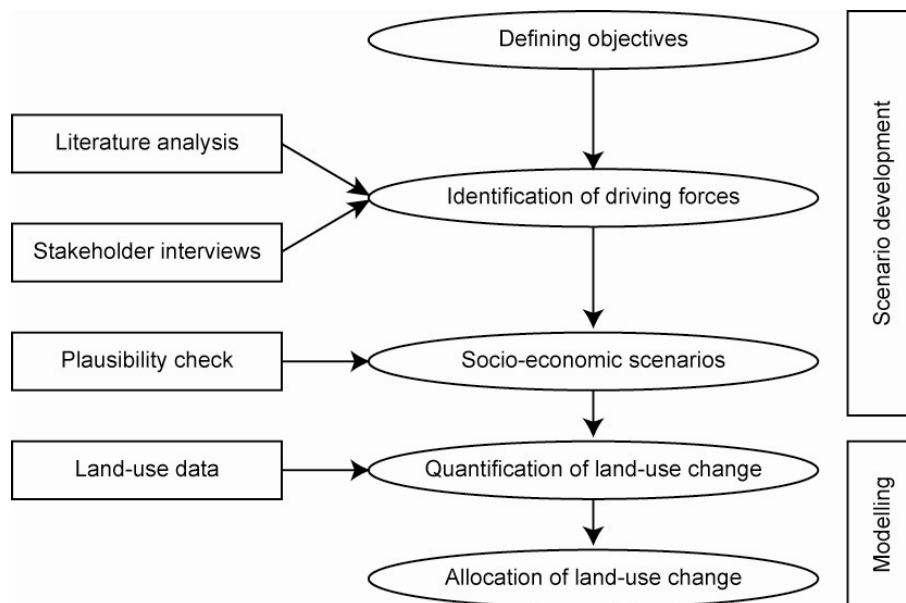


Fig. 3. Proceeding for generating scenarios.

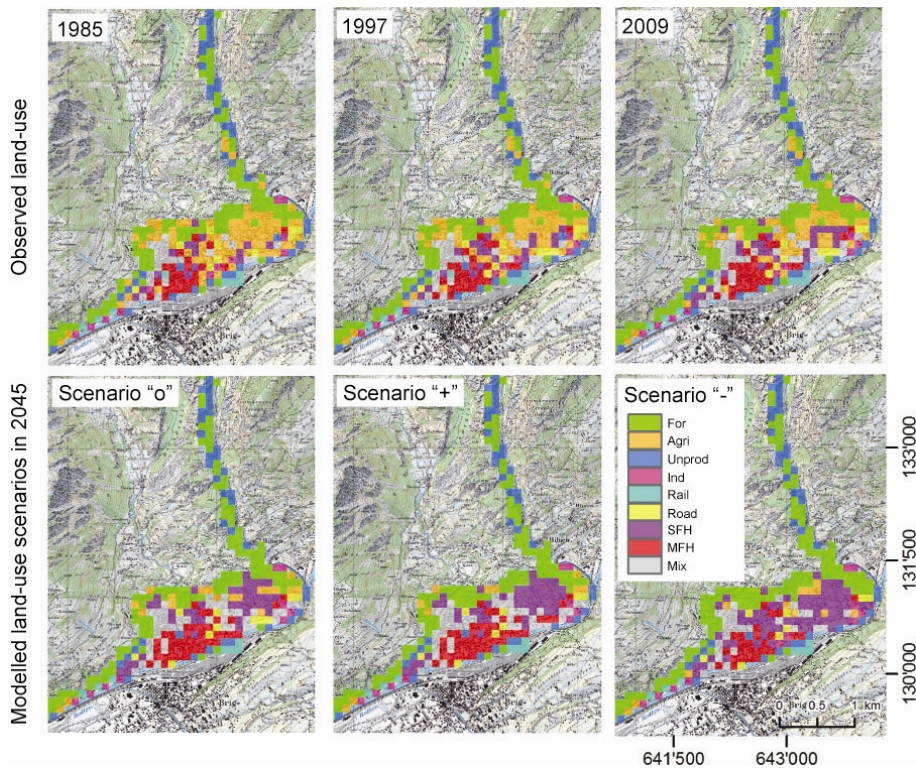


Fig. 4. Reclassified land-use data sets of 1985, 1997 and 2009 in Naters (upper row). Modelled land-use scenarios for 2045. DHM25 reproduced with permission of swisstopo (BA110005) and BFS (2012).

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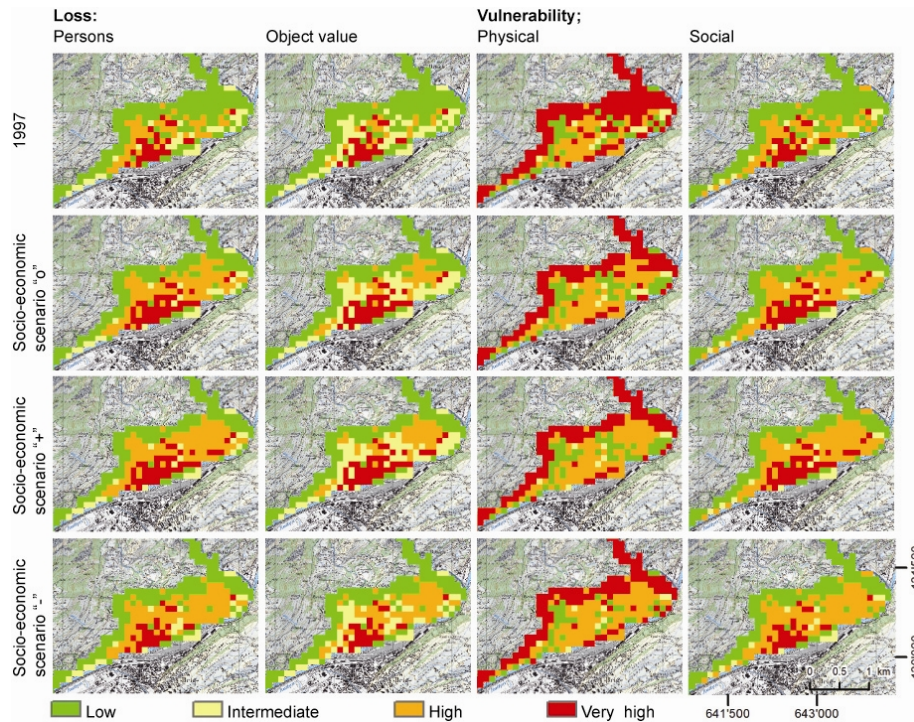


Fig. 5. Spatial allocation of the assessment variables loss and vulnerability following the four-level scale defined in Table 4. DHM25 reproduced with permission of swisstopo (BA110005) and BFS (2012).

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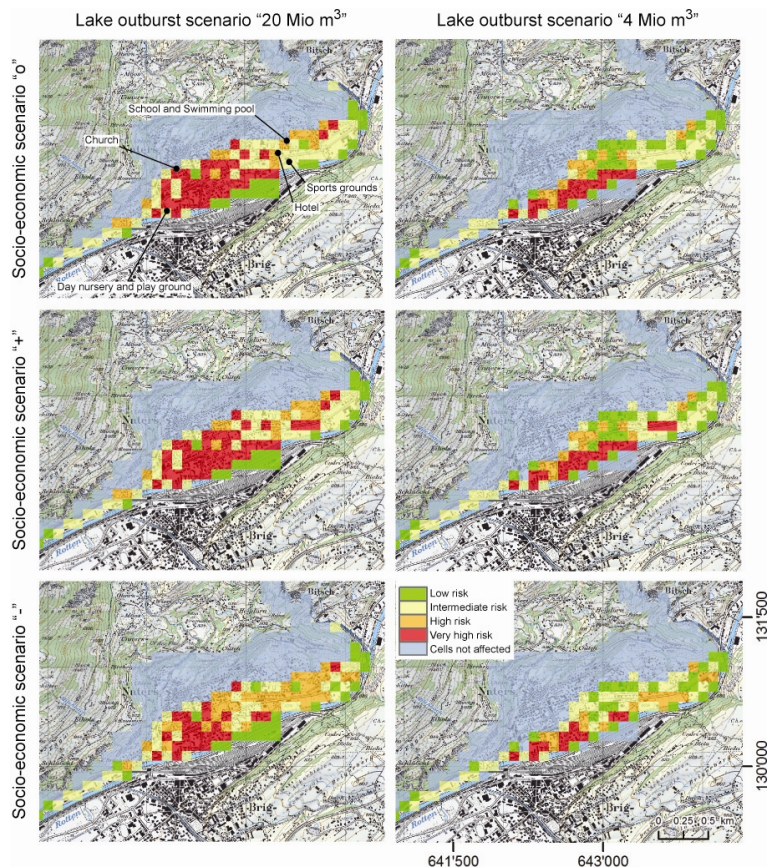


Fig. 6. Risk for Naters in 2045 in case of a lake outburst with their punctual social vulnerability (arcs). The three rows indicate the socio-economic scenarios “o”, “+” and “-”, the two columns the lake outburst scenarios with 20 million m³ and 4 million m³. Reproduced with permission of swisstopo (BA110005) and BFS (2012).

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